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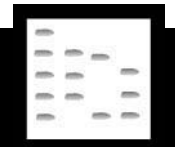
DropBooks

PHYSICOCHEMICAL MEASUREMENTS: GAS CHROMATOGRAPHY



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Introduction

Chromatography has been used for making physiochemical measurements for as long as it has been used for chemical analysis. When Martin and Synge introduced liquid–liquid chromatography in 1941 they also described how they used it to determine the distribution coefficient of the solute between the two (mobile and stationary) liquid phases.

In the early publications on gas–solid chromatography (GSC), by Wicke in 1940 and 1947 and Cremer and Prior in 1947 and 1951, the use for chemical separation is described simultaneously with physicochemical applications to the measurement of adsorption isotherms and free energies of adsorption. The earliest physicochemical measurements by gas–liquid chromatography (GLC) date from 1955 and 1956, when several authors described how to measure boiling points, partition coefficients and heats and entropies of solution for a volatile solute dissolved in a nonvolatile solvent. Since then, the scope of gas chromatographic (GC) techniques of physicochemical measurement has branched out in many different directions and now extends into a great variety of fields. These techniques are used by chemists and chemical engineers in many different specialist areas.

It is estimated that several thousand research papers have been published to date on the physicochemical applications of GC. Some of these applications have analogues in liquid chromatography, which is the subject of a separate article (Physico-Chemical Measurements).

Types of Measurement

The different types of physicochemical properties which can be measured by GC are classified in

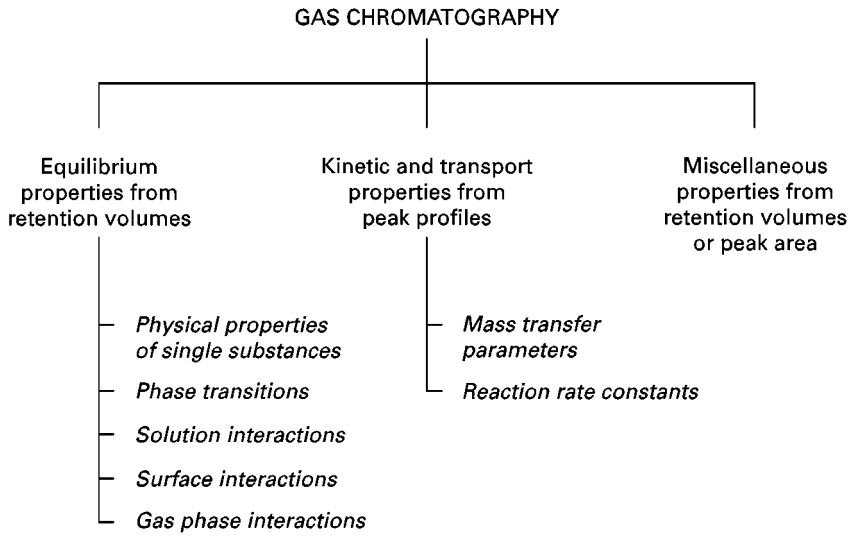

Figure 1 Classification of the physicochemical applications of gas chromatography. (Reproduced with permission from Conder, 1992.)

Figure 1 and listed in **Table 1**. They fall into three categories: equilibrium properties, kinetic and transport properties, and miscellaneous properties.

Equilibrium Properties

The largest category of properties measurable by GC is equilibrium properties obtained by measuring retention volumes. The equilibrium parameters relate to the distribution of a solute between a moving carrier gas and a stationary phase which may be liquid, solid or interfacial. (The term 'solute' is used here for all these cases.) The solute is usually injected as a small, discrete sample and its retention volume is determined. For example the activity coefficient γ of a volatile solute in a liquid stationary phase coated on an inert solid support can be determined by simply measuring the retention volume V_N of the solute and using the equation:

$$\gamma = \frac{RTW_L}{V_N p_1^0 M_L} \qquad [1]$$

where R is the universal gas constant ($8.314\,\mathrm{kJ\,kmol^{-1}\,K^{-1}}$), T is the temperature (K), p_1^0 the saturation vapour pressure ($\mathrm{kN\,m^{-2}}$) of the pure solute, W_L the mass of stationary phase in the column (kg) and M_L its molecular weight ($\mathrm{kg\,kmol^{-1}}$). For the most accurate measurements this equation is modified to incorporate a gas imperfection correction.

Besides activity coefficients, other parameters describing interactions in solution can be determined from measurements of retention volume and appropriate theoretical analyses, as listed under solution interactions in Table 1. Similarly, one can use retention measurements on suitably chosen systems of solute, stationary phase, support and mobile phase to study many surface interactions, phase transitions and physical properties of single substances, again listed in the table. A useful technique in some of these cases is inverse chromatography, where the solute is used merely as a probe to explore the behaviour of the stationary phase. This technique has been much used in investigations of polymer solutions, solid surfaces, and the various types of phase transitions listed in Table 1. Interactions between components in the gas phase are measured by varying the pressure at which the column is operated.

Kinetic and Transport Properties

Many kinetic and transport properties can be determined from the extent to which they cause a migrating solute peak to broaden as it moves along the column, or more generally from the solute concentration–time profile recorded at the column outlet. Thus, the height H (in units of length of column) equivalent to a theoretical plate can be determined by measuring the second moment σ of the peak (in time units) and the retention time t_R and using the equation

$$H = L\left(\frac{\sigma}{t_R}\right)^2 \qquad [2]$$

where L is the length of the column. It is known that H varies with carrier gas velocity according to equations such as the van Deemter equation which includes parameters such as the diffusivities of the solute in the carrier gas and liquid phase and the film

Table 1 Physicochemical parameters measured by gas chromatography

Physical properties of single substances
Latent heat
Boiling point
Vapour pressure
Phase transitions
Liquid crystals
Melting, pre-melting and post-melting transitions
Glass transition in polymers
Adsorbed liquid films
Solid–solid transitions
Solution interactions
Partition coefficient
Activity coefficient
Enthalpy and entropy changes
Complexing constants
Hydrogen bond strength
Polymer solution interactions
Solubility of gases in liquids
Solubility of liquids in liquids, solubility of (volatile) solids in liquids
Setschenow constants
Liquid–liquid distribution coefficient
Multicomponent gas–liquid equilibria
Multicomponent gas–solid equilibria
Surface interactions
Gas–solid adsorption coefficient
Surface heterogeneity
Gas–liquid interface adsorption coefficient
Gas phase interactions
Second viral coefficient of gas mixtures
Mass transfer parameters
Diffusivity in gases
Diffusivity in liquids
Diffusivity in micropores
Interfacial resistances
Adsorption and desorption rate constants
Obstruction factor
Extra-particle voidage
Reaction rate constants
In liquids
On surfaces
Miscellaneous properties
Molecular weight and average molecular weight
Surface area
Pore size distribution
Liquid film thickness
Polymer crystallinity
Structural assignment
Void zones in packed beds and rock cores
Calorific value

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thickness of the liquid phase. Consequently, these parameters can be obtained by determining H as a function of gas velocity.

Reaction rate constants are measured by several techniques. Some involve stopping or reversing the flow through the column. Others involve determining the solute concentration–time profile at the column outlet (**Figure 2**).

Miscellaneous Properties

The third and last category is a miscellaneous group of properties which can be obtained from either the retention volume, the peak profile, or the area under the recorded peak. These include molecular weights, surface areas and polymer crystallinity, as listed in Table 1.

In all the categories of physicochemical measurement so far described, the property studied is derived from measurements based on the chromatographic processes occurring in the column. There are also a few types of physical measurement in which GC is used purely as a tool of chemical analysis. These are not covered in this article though it should be pointed out that, in some cases, the analytical approach is well established, e.g. in studies of the kinetics of gaseous reactions, or of vapour–liquid equilibria by headspace analysis.

Status of GC Methods

Of the three categories of GC measurement just described, the study of equilibrium properties is the largest. This area depends on the theory of chromatographic retention which is firmly founded. Equilibrium properties are usually measurable with greater precision than other GC properties. Precisions as high as 0.05% are attainable, depending on the application and the quality of the equipment used.

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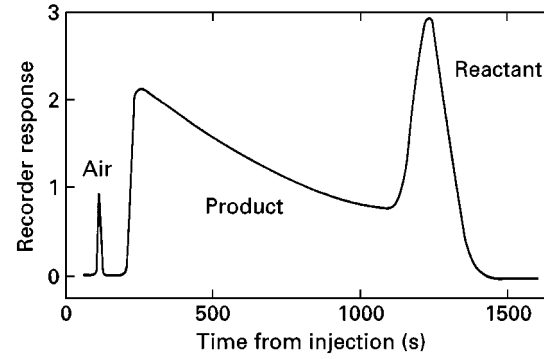

Figure 2 Illustration of the product curve method for determining reaction rate constants. The reaction is the decomposition of dicyclopentadiene in the liquid Silicone DC 550 at 190°C. The chromatogram is produced after a sample of dicyclopentadiene (reactant) is injected into a GLC column with Silicone DC 550 as the stationary phase. The reactant is adsorbed more strongly than the products and so elutes later. According to the theory of the product curve method the rate constant is found from the slope of a logarithmic plot of the product curve in the chromatogram. (Reproduced with permission from Langer and Patton, 1973.)

In contrast, measurements of transport properties such as diffusivities are much affected by the form of peak broadening model used to analyse the data. For instance, the original van Deemter equation has been superseded by more elaborate models whose relative merits have been much debated. Early studies of transport processes by GC were therefore mostly restricted to applications motivated particularly by the needs of GC itself, such as improving the efficiency of separation in analytical, preparative and production GC. Since then, however, the technique has also found wider application to rate measurements where it sometimes possesses singular advantages. Thus, certain forms of GC measurement of diffusivities provide some of the best diffusion coefficient data currently available. As a further example, studying reactions by conducting them in a chromatographic column offers the unique feature of simultaneous reaction and separation, allowing forward and back reactions to be studied directly without mutual interference, as shown in Figure 2.

Among methods of physicochemical measurement, GC offers an unusually wide range of application. Three particular roles may be distinguished:

- GC often provides an alternative to other techniques, with different advantages and disadvantages.
- GC has proved a fruitful means of discovery of new generalizations based on large volumes of data.
- GC can be combined synergistically with other techniques to shed new light on the phenomenon under study.

Examples of the first role are numerous. Thus, the most important concentration region for studying molecular interactions in solution is infinite dilution of the solute component. Non-GC methods, which depend on measuring vapour pressure, suffer from diminishing precision of measurement as infinite dilution is approached. The GC method, which depends on measurement of retention, is not inherently concentration dependent. Simple elution chromatography lends itself particularly well to infinite dilution, while several chromatographic methods, involving both elution and frontal modes of operation, are available to cover a wide concentration range up to a high mole ratio of solute in the mobile phase (**Figure 3**). As a second example, determination of mixed second virial coefficients of gas mixtures by non-GC methods, such as compressibility measurements or from pressure or volume changes on mixing, require an accurate knowledge of the second virial coefficients of both pure components. GC provides an alternative method which not only avoids this need but is more accurate.

In the second role, GC has led to the discovery of a number of valuable generalizations about the behaviour of chemical systems. For instance, it has been found that the partition coefficient of a solute in a binary mixture of two involatile liquids is very often a linear function of the volume fraction or molarity of either binary component. This has been shown to hold, with a few exceptions, for over 400 different systems (**Figure 4**). Similarly, studies have shown that the thermal behaviour of a variety of polymethylenic liquids spread on silica-type surfaces closely mimics their behaviour on the surface of water. This indicates the formation of orientated monomolecular films whose transitions have accordingly been explored by GC. In cases such as these, the value of GC lies in its speed and simplicity. Alternative methods, such as vapour pressure measurement or infrared, ultraviolet or magnetic resonance spectroscopy, are less practical for collecting the large volumes of data required. Another field of application is the correlation of retention with structure and pharmacological behaviour (QSRR).

Sometimes, results obtained by GC and other methods appear to differ. This has been observed, for example, in studies of phase transitions and adsorption at gas–liquid interfaces. In such cases the value of chromatography lies in the scientific progress achieved by trying to understand why different methods of studying apparently the same property give different results. By combining chromatographic, surface tension and gravimetric solubility measurements, for example, Martire, Pecsok and Purnell in 1965 were able to obtain unambiguous values of the average thickness of the liquid film on a porous support and resolve previous differences over the surface area and distribution of liquid on the support.

Advantages of GC Methods

As an alternative to other means of studying physicochemical behaviour, GC has its own advantages and disadvantages which depend on the applications concerned. However, certain characteristic advantages and disadvantages can be discerned. The principal advantages are enumerated below.

Speed

GC experiments are relatively fast. Local equilibrium is achieved very rapidly in the column because the interfacial area between the mobile and stationary phases is very large and path lengths for mass transfer are short. Solutes therefore usually pass through the column in minutes or even seconds. The virtue of speed provides many advantages. It is particularly valuable for solutes which are thermally unstable or have only short radioactive half-lives.

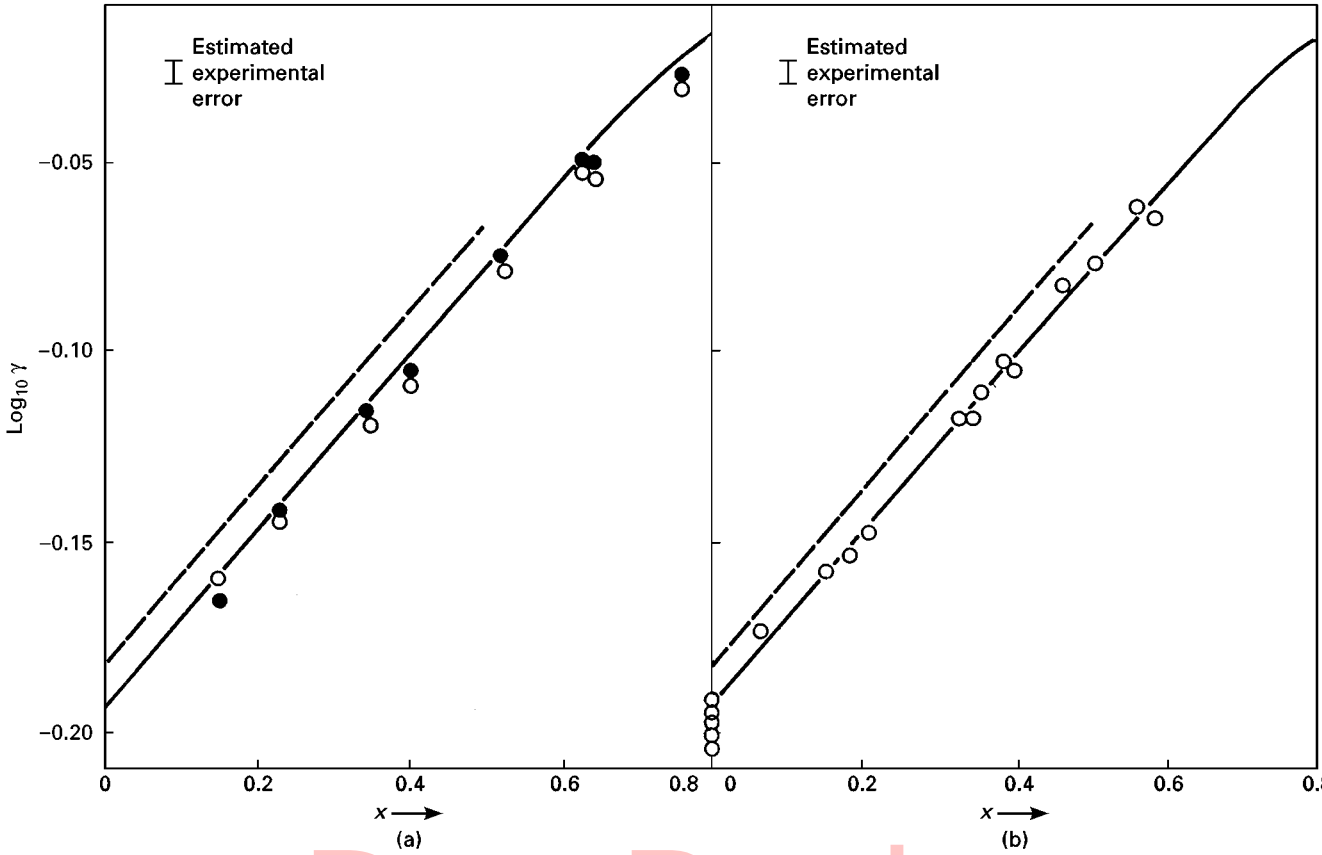

Figure 3 Example of activity coefficients in solution studied at finite solute concentrations: comparison of GC and static (gravimetric) results. The logarithm of the activity coefficient γ of the solute *n*-hexane is squalane stationary phase is plotted against mole fraction x of *n*-hexane at 30°C. (a) Chromatographic technique of frontal analysis (FA) using frontal breakthrough curves for: O diffuse front (sorption), ● self-sharpening front (desorption). (b) Chromatographic technique of elution on a plateau (EP) of constant solute concentration. Continuous curve: best line, extrapolated to $x = 0$, through static data of Ashworth and Everett (1960) obtained with squalane supported on Celite. Broken curve: static data of Martire, Pecsok and Purnell (1965) obtained with unsupported (bulk) squalane. The separation of about $2\frac{1}{2}\%$ in γ for the two static plots is small but experimentally significant and is believed to be due to the use of different samples of squalane. The results of the GC techniques are in excellent agreement with each other, with the static data of Ashworth and Everett (1960) and with further static measurements by Ashworth (1973). (Reproduced with permission from Conder and Purnell (1969) *Transactions of the Faraday Society* 65: 839. Copyright Royal Society of Chemistry.)

Experimental time can often be saved by injecting a mixture of several solutes of differing retentions in one run. Work requiring large amounts of data can be conducted within a reasonable timescale.

Contact times can be kept short. When adsorption on catalysts is studied by static methods, the problem is to observe it despite the accompanying presence of decomposition. The temperature has to be far below the normal operating temperature of the catalyst to avoid excessive decomposition during the experiment. With elution GSC the temperature can be near the normal operating temperature because of the short contact time between 'solute' (adsorbate) and adsorbent at each point in the column. Low contact time is also beneficial in studying adsorption on polymer surfaces. Here static measurements do not distinguish between surface adsorption and bulk adsorption. GSC allows the rapid adsorption process to be examined without interference from the slower adsorption process.

Small Amounts of Material Required

GC measurements at infinite dilution require only very small amounts of solute, e.g. 100 μg, but as little as 10^{-11} g can be used if necessary. This is a particular advantage for solutes that are available only in trace amounts. The amount of stationary phase needed is also relatively small – 2 g of liquid is typical in a packed column but 1 mg of liquid can be used in a capillary (open tabular) column.

Impure and Mixed Solutes

Solute mixtures or impurities are usually separated on the column, and so can be run without previous purification.

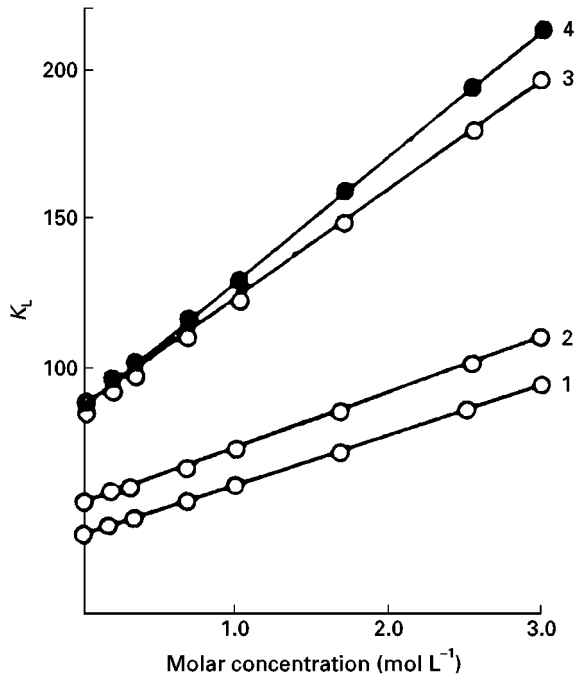

Figure 4 Example of linear plots of gas–liquid distribution coefficient K_L of solutes against molar concentration (mol L^{-1}) of di-*n*-butyltetrachlorophthalate in squalane at 80.3°C. Data of Eon, Pommier and Guiochon. The solutes are: (1) 2-methylfuran, (2) 2,5-dihydrofuran, (3) benzene and (4) thiophen. (Reproduced with permission from Purnell and Vargas de Andrade (1975) *Journal of the American Chemical Society* 97: 3585. Copyright American Chemical Society.)

Reactive Solutes

GC methods are often preferred for reactive solutes because separation of reactants and products on the column allows the forward reaction to be studied alone without interference from the reverse reaction or from autocatalysis or product inhibition. Additionally, contact times are short, quantities small and fewer difficulties are encountered with reaction with the materials of construction of the equipment.

Wide Temperature and Pressure Range

Change of temperature is much more easily accomplished in a chromatograph than in most volumetric or gravimetric techniques. Additionally, because the column is of small diameter and compact, extremes of temperature and pressure can be achieved more readily than by many other techniques, e.g. below 100 K, above 1200 K, or up to 2000 bar.

Characteristics of GC Methods

Despite the advantages of GC methods, there are also several characteristic limitations inherent in the technique which need to be appreciated for reliable measurement. Much effort has been expended in overcoming these limitations. On the whole considerable success has been achieved, though often at the expense of complicating the technique. We will consider five characteristics of the method: interference between interactions under study, stationary phase volatility, the number of components in the system studied, the influence of the 'inert' carrier gas and the influence of the support.

Interference Between Interactions Under Study

The remarkable versatility of the method seen in Table 1 is partly due to the large number of components characteristically present in a chromatographic column. A GLC column contains at least three bulk phases (gas, liquid and solid) and two interfacial phases (gas–liquid and liquid–solid; the gas–solid interface is seldom problematic in GLC). Potentially, therefore, the study of one interaction may be complicated by the presence of another. Common examples of interfering processes are adsorption on the solid support and/or adsorption at the gas–liquid interface during studies of interactions in solution. The adsorption increases the retention volume from which the solution parameters are to be determined. Sometimes it is possible to avoid or minimize the interference by suitable choice of support. If not, procedures have been devised involving varying the loading of liquid phase on the support and plotting the data in such a way as to determine both the solution and adsorption parameters.

Influence of the Solid Support

This is the commonest example of the interference problem just described. Physicochemical measurements are usually made with packed columns. In GLC a solid support is used to hold the stationary phase as a liquid of high surface area. It is seldom safe to treat the support as completely inert. Adsorption of solute by the support often causes 'tailing' of polar solutes. It is not always appreciated that support adsorption may still affect solute retention even when no tailing is observed. Reproducibility of the support was a serious bar to reproducible data in early GC work. Support adsorption can be detected and eliminated by varying the liquid loading and analysing the data appropriately. This is a desirable procedure in all GLC measurements of solution equilibria unless there is already good evidence that adsorption by the support is negligible. It is usually found that support adsorption can be neglected with nonpolar organic solutes. In other cases one can either greatly reduce the effect by chemically reacting the support surface with a silanizing agent, or eliminate the effect by

appropriate data analysis of measurements at different liquid loadings.

Volatility of the Stationary Phase

By its nature, GC is well suited to studying binary systems involving one volatile component, the solute, and one involatile component, the liquid or solid stationary phase. The technique may be extended to volatile stationary phases with vapour pressures up to about 3 bar, either by the well-established approach of pre-saturating the carrier gas with vapour of the stationary phase, or by a technique of nonsteady-state gas chromatography recently developed for the purpose.

Multicomponent Systems

In simple chromatography with an inert carrier gas, there are often only two active components, the volatile solute and a single-component, involatile, stationary phase, together forming a binary system. Two types of multicomponent system can also be studied. In the first, there are two or more involatile components in the stationary phase. This type of multicomponent system is met in studying complexing behaviour in solution. It presents no new problems of technique though the analysis of the data is of great thermodynamic interest. In the other type of multicomponent system more than one volatile component is involved in the liquid phase interaction. In this case one of the two volatile components must be introduced at a steady concentration into the carrier before entry to the column, and the other solute is injected as a discrete sample. This method has been used to study multicomponent gas–liquid and gas–solid equilibria at high pressures.

Influence of the 'Inert' Carrier Gas

Although the carrier gas is often thought of as inert, several interactions involving the carrier and solute occur in the gas phase. The combined contribution to the measured retention of solute is of the order of 1–5%. This is usually known as the gas imperfection correction. It needs to be calculated and corrected for in studies of adsorption or solution equilibria making any claim to accuracy. The correction was often omitted or incorrectly calculated in early studies and invalid versions of the correction are still sometimes quoted in current publications.

Apparatus Requirements

Most physicochemical measurements by GC are conducted with packed rather than open tubular (capillary) columns. The very high resolution offered by open tubular columns is of little benefit for most physical measurements. Determination of the mass of stationary phase in the column is easier and more accurate with packed columns.

The type of GC apparatus needed for physicochemical measurements depends on the precision of measurement desired, which varies with the application. A commercial instrument is often suitable for simple physical properties such as latent heats, boiling points and vapour pressures, where the role of GC is to provide a method of obtaining large amounts of data rapidly. The control of column temperature may be of high precision but poor accuracy with a commercial chromatograph, but with improved instrumentation of pressure and flow rate, is also appropriate for most measurements at infinite dilution of the solute. For work at finite concentrations of the solute, however, it is necessary either to inject especially large samples of solute or to pass into the column a steady concentration of solute in the mobile phase. Various forms of finite concentration technique have been developed. Almost all require a purpose-built instrument or a specially modified commercial unit. Studies of gas phase interactions, which entail elevated pressures, also require specially built GC equipment.

DropBooks

Measurement of Separation Process Data

In the design of process plant a variety of data is needed on the properties of substances, particularly in designing separation and reaction processes. Chemical engineers are not always as aware as chemists of the suitability of GC methods for obtaining property data, but the potential is considerable. Of the parameters listed in Table 1, those particularly relevant to process engineering include physical properties of single substances, activity coefficients in solution, gas solubilities, liquid–liquid distribution coefficients, multicomponent equilibria, adsorption coefficients, diffusivities, mass transfer parameters, reaction rate constants and some of the miscellaneous properties.

See also: **II/Chromatography Gas:** Column Technology; Historical Development; Theory of Gas Chromatography.

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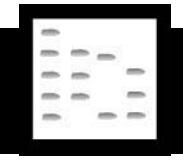
pH-ZONE REFINING COUNTERCURRENT CHROMATOGRAPHY



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What is pH-zone-refining Countercurrent Chromatography (CCC)

This countercurrent chromatography (CCC) technique distributes large quantities of ionic analytes (acids and/or bases) into a train of rectangular peaks of very high concentrations with high purity. The method utilizes ionic interaction between analytes to shift their partition coefficients according to pK_a and hydrophobicity.

Development of pH-zone-refining CCC

In liquid chromatography, isocratic elution usually produces symmetrical peaks where the peak width increases with retention time. In the course of purification of $BrAcT_3$ (*N*-bromoacetyl-3,3′,5-triiodo-L-thyronine) by high-speed countercurrent chromatography (HSCCC), it was found that the product formed an unusually sharp peak corresponding to over 2000 theoretical plates, while the preceding impurity peak showed a normal width of about 500 plates. The cause of this sharp peak formation was finally found when the collected fractions were manually analysed for pH. As shown in **Figure 1**, the pH-curve showed a gradual decline after the solvent

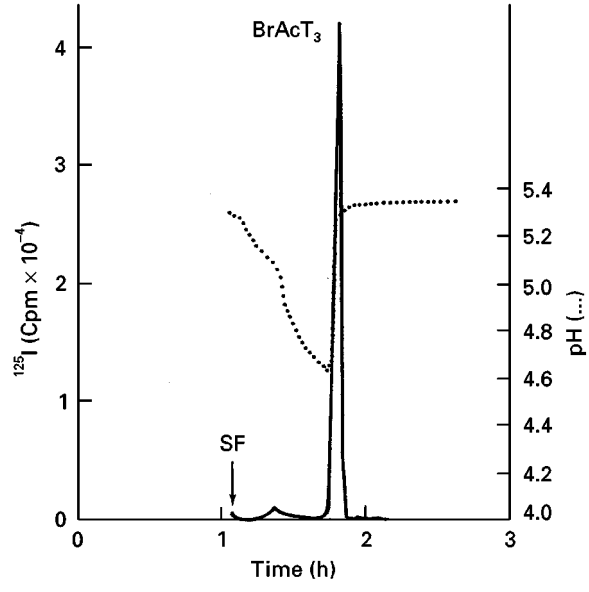

Figure 1 Disclosure of the cause of sharp peak formation by manual pH measurement. Sample: CCC-purified $BrAcT_3$ (approximately 0.1 mmol) + blank bromoacetylation mixture. The elution of the sharp peak coincides with the abrupt rise of the pH suggesting the acid in the sample solution as the cause of the peak sharpening.